PB-216 548

USE OF CHEMICAL ADDITIVES TO IMPROVE AERATION RATES. PRELIMINARY STUDY OF MODELS

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1966

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University of Maine

Progress Report 2b

Use of Chemical Additives To Improve Aeration Rates

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Preliminary Study of Models

by
STEFAN A. ZIEMINSKI
and
MARTIN E. RAY

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U. S. Department
of
Health, Education, and Welfare

PUBLIC HEALTH SERVICE
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UNIVERSITY OF MAINE

PROGRESS REPORT NO. IIb

USE OF CHEMICAL ADDITIVES TO IMPROVE AERATION RATES

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PRELIMINARY STUDY OF MODELS

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I

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ABSTRACT

Previous investigations (1,2) conducted with porous plates have shown that some organic substances present, in minute quantities, in the aerated mixture increase the interfacial surface area (A) to such an extent that despite the reduced mass transfer coefficient (K_L) the total rate of oxygen transfer (K_LA) can be considerably increased. It was also found (2) that the increase in the surface area depends on the concentration of the agent in the zone of bubble formation and once small bubbles are formed they tend to maintain their small size even if the concentration of the agent in the bulk of the liquid is much smaller.

The report deals with a preliminary investigation of three different models of aerators in which the organic agent was introduced at different rates of flow and concentrations. The objective of the tests was to obtain some information about the effects of these variables on quantities such as the bubble diameter, the interfacial area, the mass transfer coefficient, and the total rate of oxygen transfer.

The results of this preliminary investigation are summarized at the end of the report.

INTRODUCTION

Study of oxygen absorption from air bubbles produced by porous plates has shown that small quantities (1 to 5 ppm) of some organic substances may considerably increase the rate of oxygen transfer (1,2,3).

In a previous investigation (2) it was noticed that this effect depends to a great extent on the concentration of the substance in the zone of bubble formation. Once the small bubbles are formed, they tend to maintain their size even though the concentration of the substance in the bulk of the aerated liquid is much smaller. In order to study this effect, two ways of approach were suggested for investigation.

In the first approach, the investigated substances were introduced in the form of vapor together with the stream of air. Despite a wide range of concentrations applied, no change in the size of air bubbles was observed in any of these tests and investigation in this direction was discontinued.

In the second approach, the solution of the material under study was continuously introduced at the air dispersing surface located in a stream of water flowing vertically. In this way, a zone of higher concentration was produced at the air disperser. This method of introduction proved to be more effective than operation in a uniform solute concentration (2); that is, a lower bulk concentration was required to produce the same increase in the rate of oxygen transfer $[K_L A]$. It was also noticed that operating in a continuous system at the same bulk concentration of the substance, the rate of oxygen transfer depends on the concentration and the rate of flow of the solution entering the air dispersing surface.

The objective of this work was to continue this investigation with the

use of different air dispersing systems in which the agent is continuously introduced into the zone of bubble formation.

Because of lack of more accurate information, three dispersing systems were arbitrarily selected for preliminary investigation.

THE AIR DISPERSING SYSTEMS

Model I. The Rotary Disperser (See Figure 1).

The disperser consisted of two concentric hypodermic needles inserted in the hollow shaft of an electric motor. The needles were 713 and 718 gage and their upper ends were bent at a 90° angle forming a straight arm 0.84 inch long. The lower end of the inside needle was allowed to extend about 2 inches below the end of the outside needle. The air was introduced into the inside needle by means of a rubber gland. The solution of the agent was passed through a similar gland into the annulus between the two needles. The tests were conducted at a constant speed of the motor of 1690 rpm, corresponding to a peripheral velocity of 3.79 m/sec at the tip of the needle. The aerator was mounted in the bottom of a cylindrical absorption column at a distance of 6 cm above the bottom. A rubber gland similar to those used for the air and solution insured leak-free operation of the column.

The purpose of this disperser was to inject the solution together with air and to create a zone of a higher solute concentration at the rotating tip of the needle. It was realized that this local concentration depends, for a given solute flow, on the rate of mixing, which in turn is a function of the speed of the aerator. However, to avoid complication, no provision

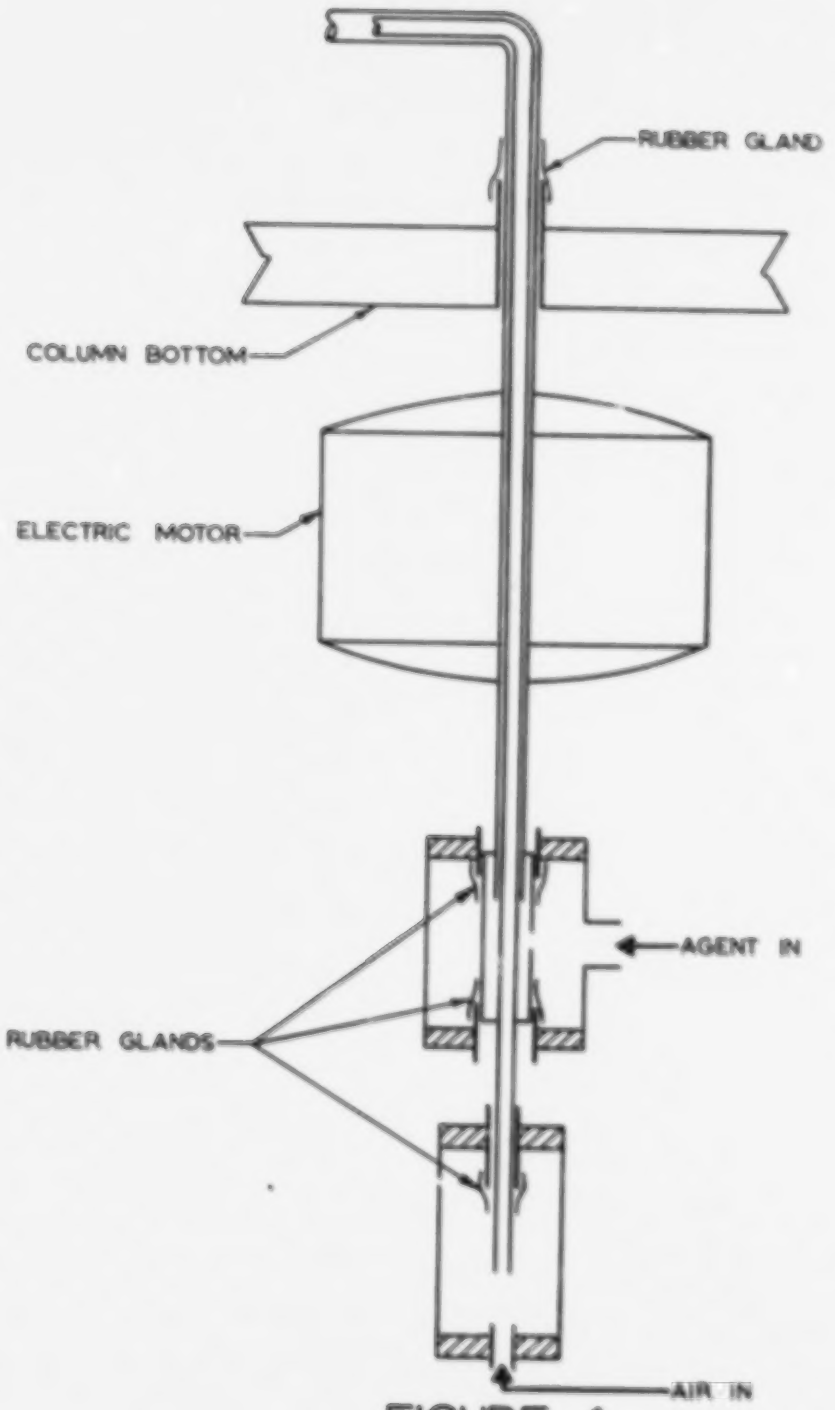

FIGURE 1
ROTARY AERATOR

was made for varying the speed of the aerator motor.

To prevent coalescence of the bubbles in the wake of the rotating arm a small metal plate was attached to the tip of the needle.

Model II. Porous Plate.

This system consisted of an Aloxite porous plate (grade 2), 8 mm in diameter, and a glass tube mounted above the center of the plate, for introduction of the agent. The purpose of this arrangement was, as in the previous model, to establish a higher solute concentration at the dispersing surface. To what extent this could be achieved would depend on the rate of flow and concentration of the entering solution and on the degree of mixing induced by the rising bubbles.

Model III. Aloxite Plate with Collar (Figure 2).

This system is similar to Model II except for a cellophane collar extending 1.5 cm above the surface of the plate. The purpose of this modification was to decrease the degree of mixing of the agent solution with the surrounding liquid and thus maintain a higher concentration at the surface of the porous plate.

THE EXPERIMENTAL PROCEDURE

The operation of the models was investigated in a plexiglas absorption column 51 cm high and 12.5 cm in diameter (Figure 3). One side of the column was removed and replaced with a flat sheet of plexiglas 8 cm wide. This was done to avoid optical distortion while photographing the bubbles. The dispersers were mounted in the center of the bottom plate of the column. A plastic baffle was installed across the column, three inches above the

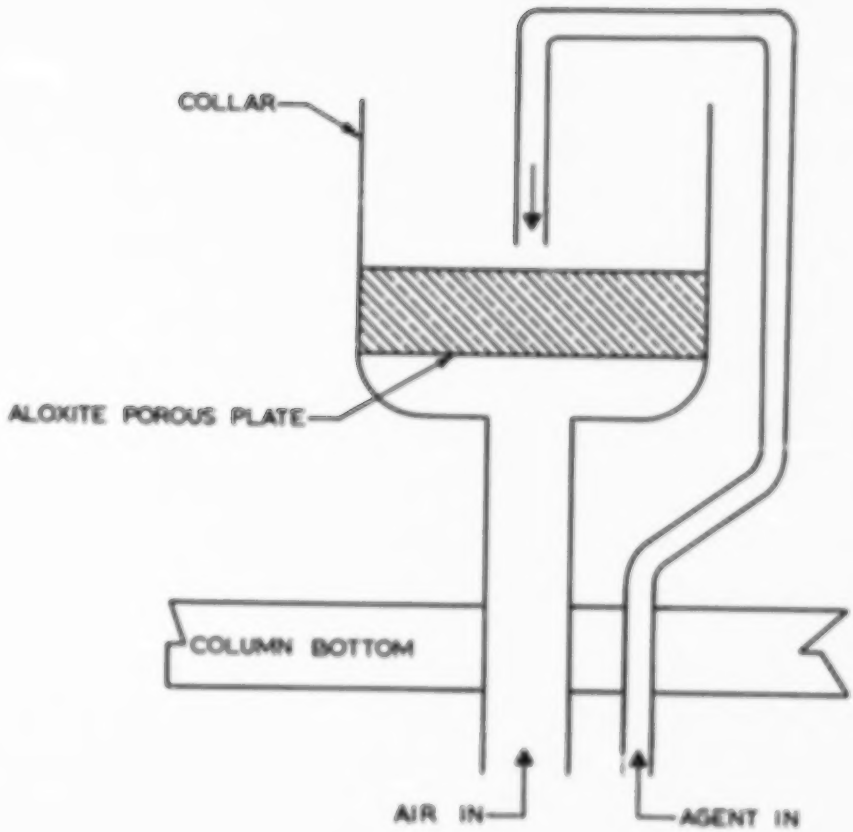

FIGURE 2
POROUS PLATE WITH COLLAR

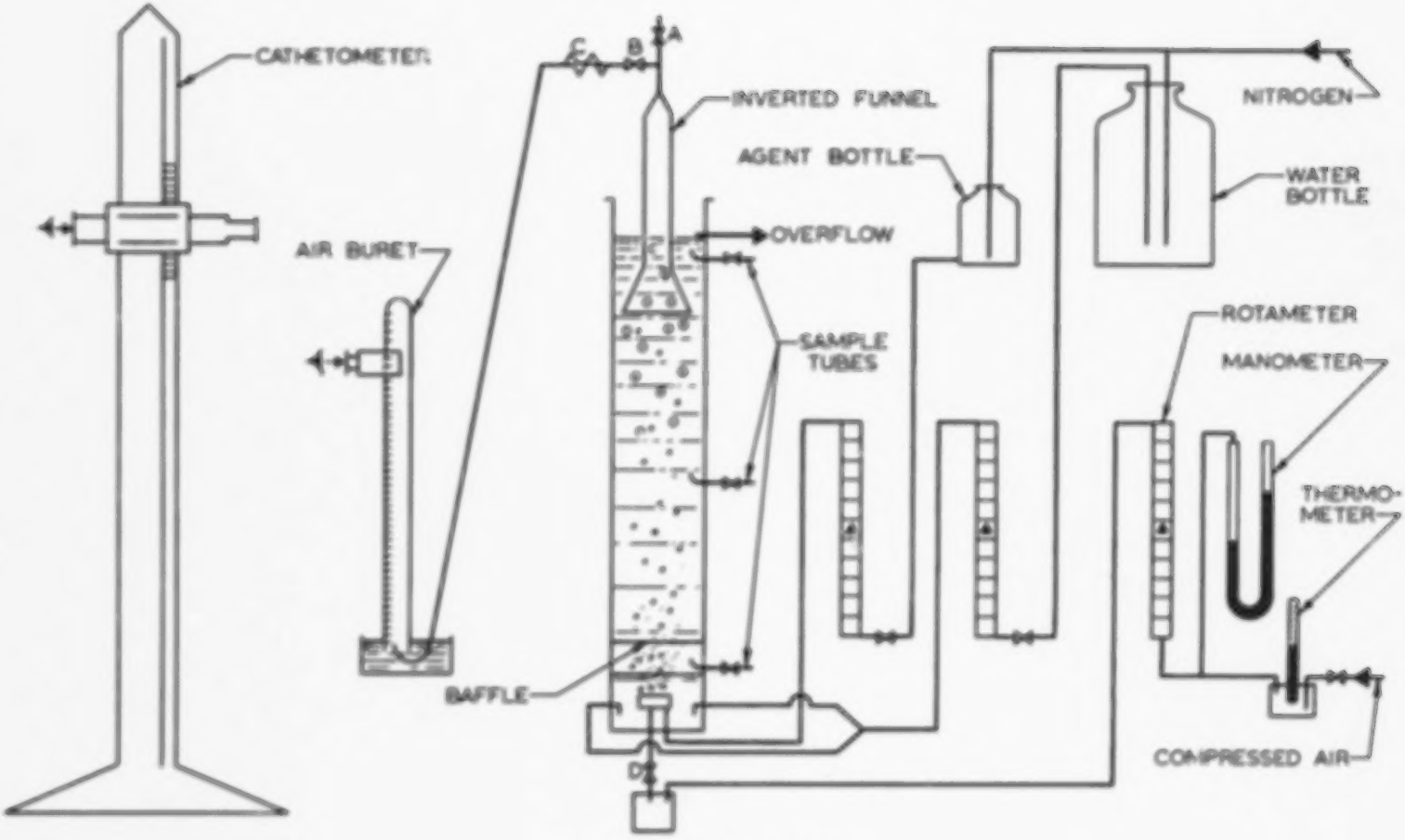

FIGURE 3
DIAGRAM OF TEST EQUIPMENT

bottom, to prevent formation of a vortex when using the rotary disperser. Compressed air from a cylinder was introduced through a rotameter and a small connecting vessel into a tube leading to the disperser. The column was operated both batchwise and continuously. All the tests were conducted at 25°C.

In the continuous operation, water, deoxygenated by means of nitrogen, was introduced at a measured rate into the bottom of the column and left at the top through an overflow opening. In order to decrease surface aeration, the column was covered and a small stream of nitrogen was introduced over the surface of the water. The agent solution in deoxygenated water was passed through a flowmeter into a tube leading to the disperser. During the test, nitrogen was bubbled through both the water and solution to prevent air from entering the respective containers. An air flow rate of 156 cc/min (STP) was used in all the absorption tests. The total combined flow of the solution of the substance and water was 500 cc/min and constant in all the tests. At 10, 15 and 17.5 minutes from the time the water filled the column, samples were taken from the top sampling tube for dissolved oxygen (D.O.) determination. This was done to check if the steady state had been reached. After 18 minutes, all flows to the column were stopped, the contents of the column were rapidly mixed by a few strokes of a plunger type stirrer and a sample of water was taken from the bottom sampling tap (C_b). The D.O. concentration of the water entering the column (C_o) was also determined during the test. The bulk and the initial D.O. concentrations were used in the calculation of the rate of oxygen absorption in the continuous system.

In the batch operation the column was first filled with distilled water to the 5400 cc mark and its temperature brought to 25°C. After deoxygenation

by means of nitrogen, the first D.O. sample was taken and the volume of water in the column was adjusted to 5100 cc. Similarly to the continuous operation, an air flow rate of 156 cc (STP) was used in all tests of this group.

At 2 minute intervals samples of water were taken for D.O. determination. The duration of the test was 10 minutes. The results were plotted against time and the resulting absorption curve was used in the calculation of the rate of oxygen transfer.

The Interfacial Area. The surface area of transfer was calculated from the measurements of the gaseous hold-up and the size of the bubbles. The gaseous hold-up was determined by collecting the air under an inverted funnel and measuring its volume in a gas buret.

The size of the bubbles was estimated by means of a photographic technique. A Polaroid camera with a close-up lens was used in taking the pictures. A stroboscope was connected to the camera by means of an electronic flash adapter. A flash of 3 micro-seconds was produced when the shutter was triggered. The film (46-L transparency) was projected and the actual sizes of the bubbles were determined from projection of a standard of a known size.

The details of the photographic procedure and the gaseous hold-up measurement are discussed in our previous Progress Report (3).

The interfacial area was calculated for oblate spheroids from the measured major and minor axes of the bubbles and the gas hold-up. The total number of bubbles was calculated by dividing the hold-up by the bubble volume. Subsequent multiplication of the total number of bubbles by the surface area of the spheroid gives the total interfacial area, A:

$$A = \frac{3H\left(2 + \frac{1 - \alpha^2}{\alpha} \ln \frac{1 + \alpha}{1 - \alpha}\right)}{4b} \qquad (1)$$

H = Total air hold-up, cm^3

b = Minor semi-axis, cm

a = Major " , cm

α = Eccentricity = $(1 \quad (\frac{b}{a})^2)^{1/2}$

A = Total surface area, cm^2

To evaluate the reproducibility of this procedure, tests were conducted with continuous flow of distilled water using the rotary aerator. From these tests, the interfacial surface area was found to be 551.5 cm^2. The probable error attached to this value was ± 7.4 cm^2, and the probable error of each determination was ± 14.7 cm^2.

Calculation of the Mean Transfer Coefficient K_L. The methods for the calculation of K_L vary depending on whether the continuous or batch absorption system is used.

In the continuous system, the mass transfer coefficient was calculated from equation:

$$K_L = \frac{q}{A(C_e - C_b)} \qquad (2)$$

where q is the oxygen absorption rate defined by:

$$q = \frac{V(C_f - C_o) \times 60}{10^6} \qquad (3)$$

V is the rate of flow of water and C_o, C_e, C_f, and C_b are the respective D.O. concentrations at time zero, at equilibrium, at overflow, and in the bulk of the liquid.

From a number of tests the $K_L A$ value for water was found to be 0.0498 g O_2/(hr)(ppm). The probable error attached to this value was ± 0.0006, and the probable error of each determination: ± 0.0012.

In the batch system containing W g of water, the K_L can be calculated from:

$$K_L = \frac{W}{10^6 A} \frac{\ln(C_e - C_o)/(C_e - C_b)}{t} \qquad (4)$$

which is obtained by integration of the basic mass transfer equation on the assumption that C_e and A are independent of time (3). The interfacial surface area was calculated by a method analogous to that used in the continuous system.

The reproducibility of the K_L determination was checked in distilled water using the rotary aerator. From these tests, K_L for water was found to be 0.870×10^{-4} g/(hr)(cm^2)(ppm). The probable error attached to this value was $\pm 0.020 \times 10^{-4}$, and the probable error of each determination was $\pm 0.035 \times 10^{-4}$.

The Bubble Diameter. The bubble diameter used in this work is the surface-volume mean diameter (or Sauter diameter) d_s defined as:

$$d_s = \frac{6H}{A} = \frac{\sum nd^3}{\sum nd^2}$$

where H and A are the total gas hold-up and the total interfacial area respectively and n and d are the number and diameter of the bubbles.

DISCUSSION OF RESULTS

The Rotary Aerator (Model I)

In order to determine the merits of this system the performance of the aerator was investigated under continuous flow and batch operation conditions. Normal amyl-alcohol was used as the organic additive.

In the continuous system, the solution of alcohol was introduced into the aerator and discharged together with the stream of air. The rate of flow of the solution was 10.9 cc/min and was kept constant in all tests of this group. By keeping the total flow through the column constant and varying the concentration of the entering solution, any required bulk concentration of the alcohol could be easily obtained.

When using the batch system, no alcohol solution was introduced into the aerator and the required bulk concentration in the column was obtained by addition of the alcohol to water prior to the beginning of the test.

Figures 4 to 7 compare the performance of the aerator at the same bulk concentrations of alcohol but, in one case, with the continuous flow of the alcohol solution through the aerator, and in the other case, with no alcohol flow (batch system). It can be seen from Figures 4 and 5 that there is not much difference between the two systems as far as the size of the bubbles and the surface area are concerned. However, at concentrations above 6 to 8 ppm, the continuous flow system gives smaller bubbles and somewhat larger surface areas than the batch system. The reverse is true at lower concentrations.

The mass transfer coefficient, K_L, as well as the total oxygen transfer relative to water, $[K_LA]_R/[K_LA]_W$, are considerably higher for the batch system except at concentrations below 3 ppm.

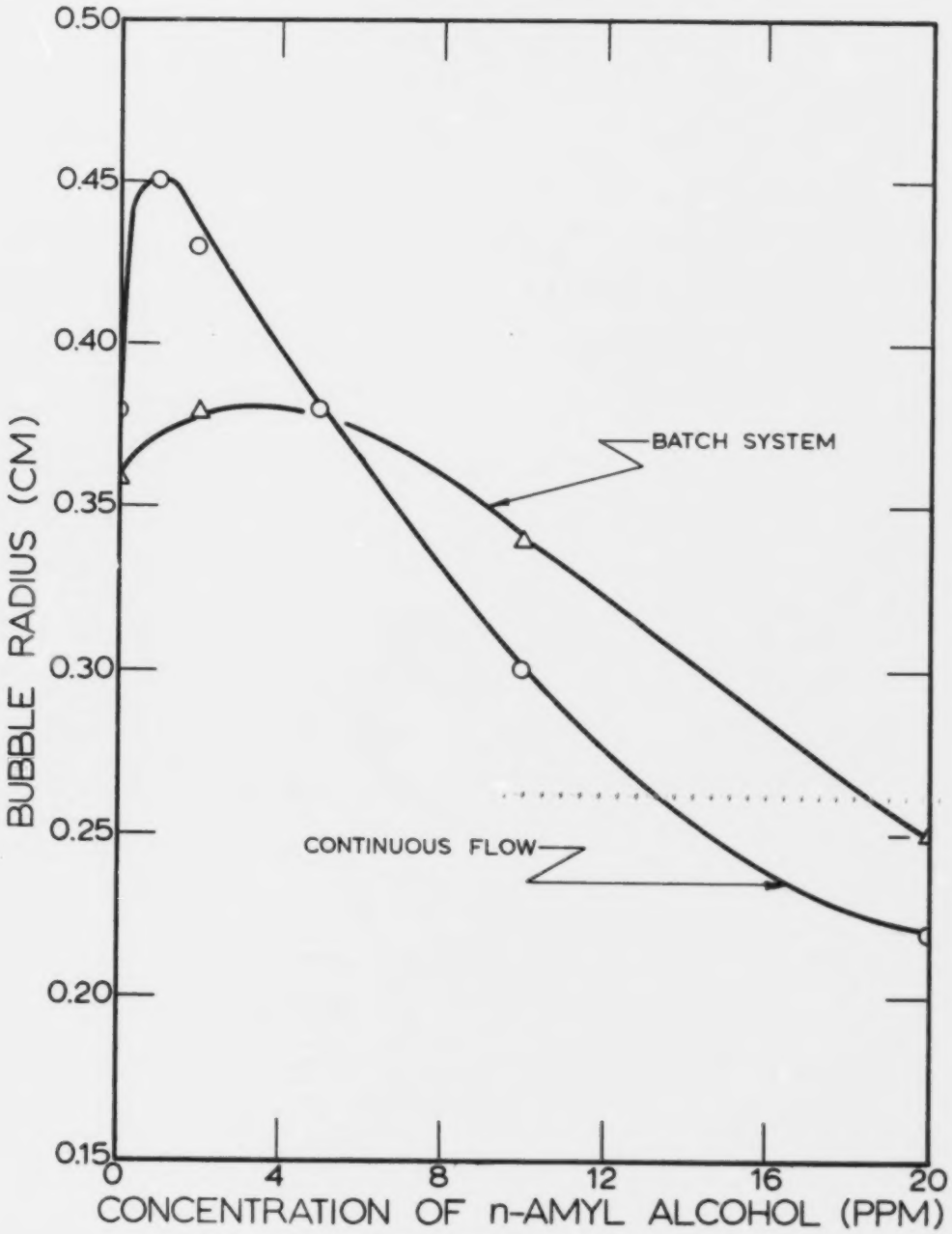

FIGURE 4
BUBBLE RADIUS vs CONCENTRATION OF
n-AMYL ALCOHOL
ROTARY AERATOR

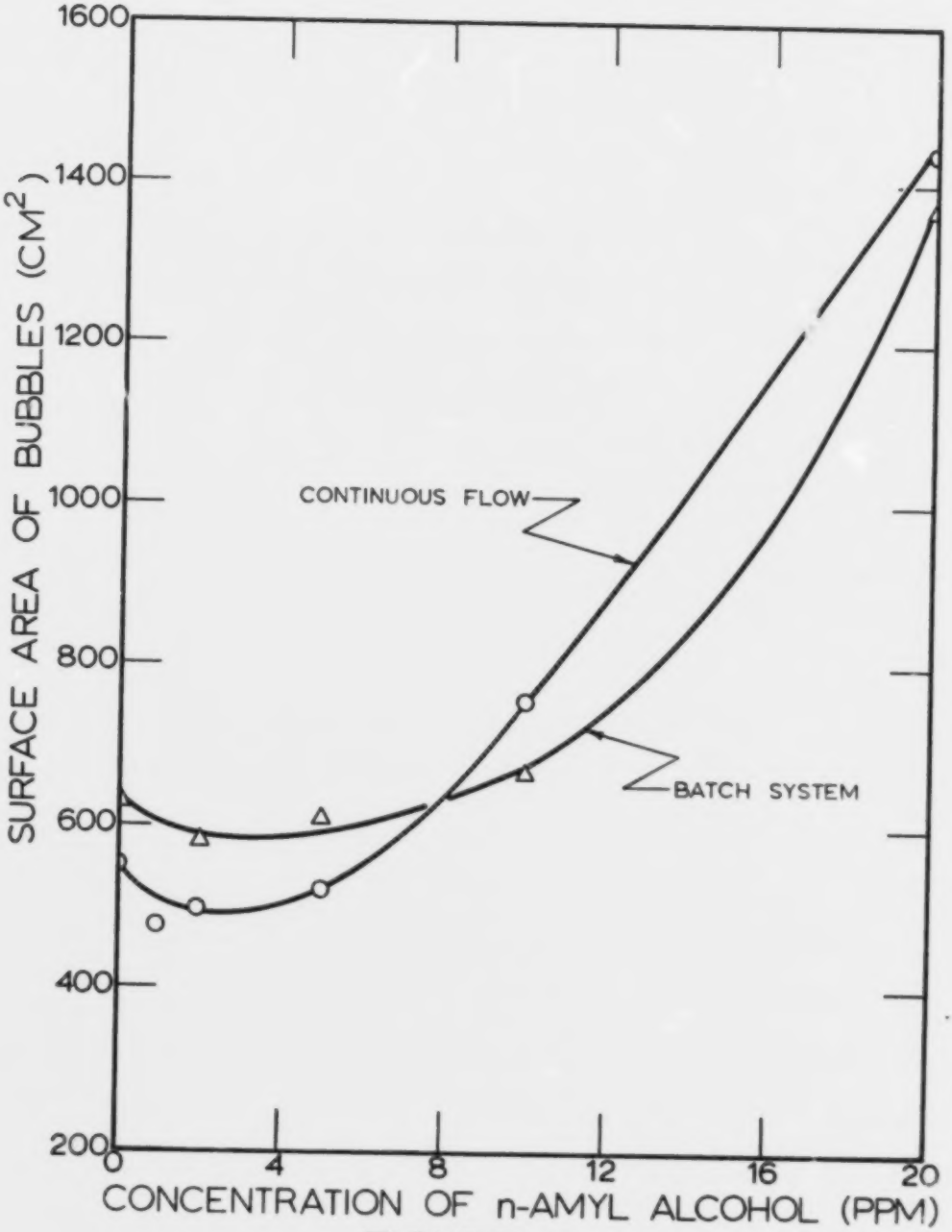

FIGURE 5
SURFACE AREA OF BUBBLES vs
CONCENTRATION OF n-AMYL ALCOHOL
ROTARY AERATOR

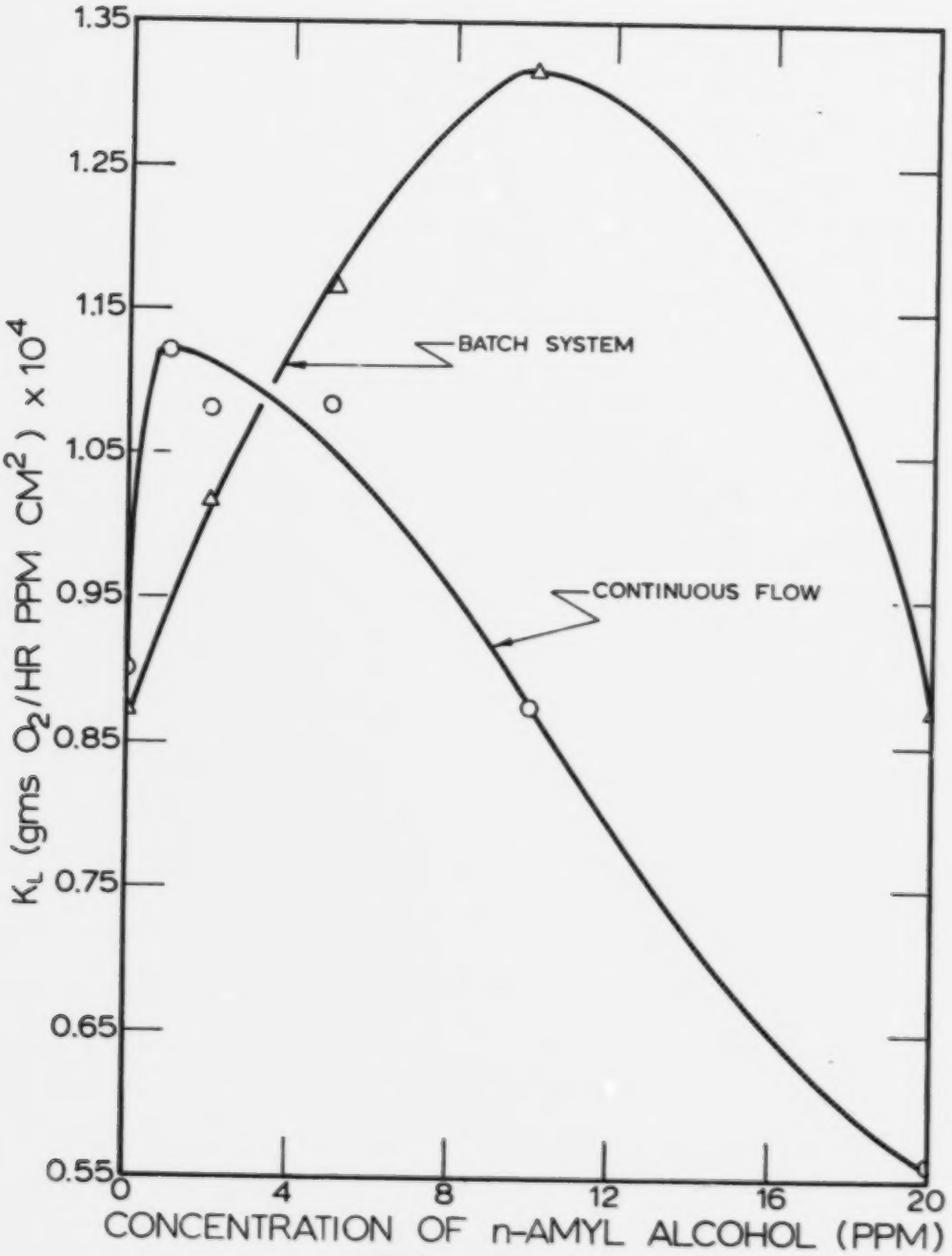

FIGURE 6
K_L vs CONCENTRATION OF
n-AMYL ALCOHOL
ROTARY AERATOR

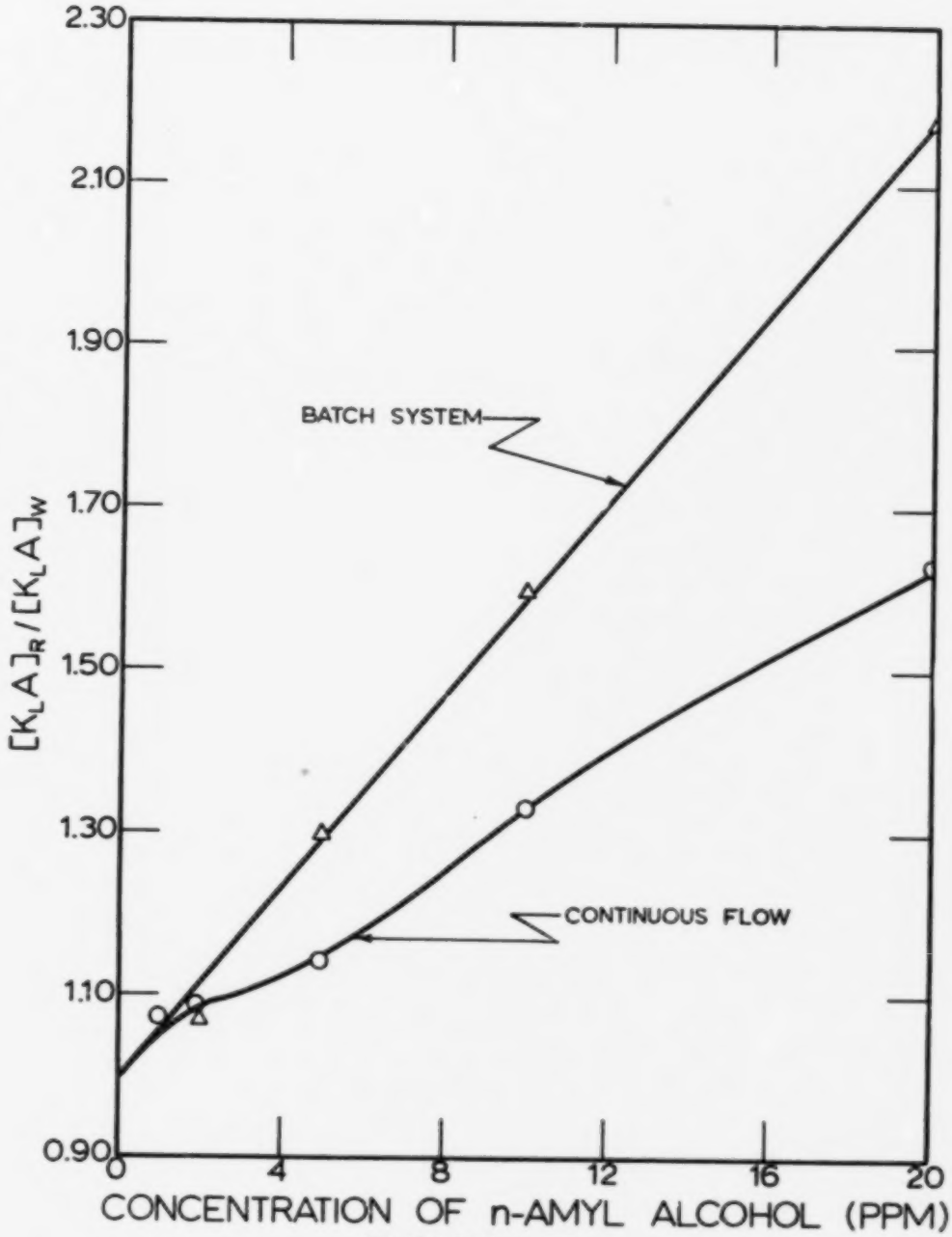

FIGURE 7
$[K_LA]_R/[K_LA]_W$ vs CONCENTRATION OF
n-AMYL ALCOHOL
ROTARY AERATOR

It appears therefore that the simultaneous introduction of the agent and air in a rotary system is actually harmful to the process, principally because of the substantial drop in the mass transfer coefficient which was not counterbalanced by the comparatively small increase in the transfer area.

It is possible that under the conditions of the test the rate of dilution of the solution leaving the aerator was so fast that the resulting small concentration was not enough to produce a substantial decrease of bubble coalescence and therefore a larger interfacial area.

Stroboscopic examination has also shown that the bubbles are not formed at the tip of the aerator but are detached from the stream of air at some distance from the tip, where the concentration of the agent is already low.

Although the results obtained with this model were not encouraging, it must be stressed that the tests were conducted only at one aerator speed and at one flow rate of the solution. It is possible that an appropriate change of these two operating conditions could improve the results.

The Aloxite Plate (Model II)

Figures 8 to 11 show the results obtained with the porous plate using a continuous flow of dilute alcohol solution over the surface of the plate. The tests were conducted at the rates of flow of the alcohol solution of 10 and 40 cc/min and at bulk alcohol concentrations between 0 and 5 ppm. The concentrations of the alcohol solutions were so adjusted as to produce, at the different flow rates, the required bulk concentrations. It can be seen from Figures 8 and 9 that for a given bulk concentration the size of the bubbles and their surface areas are not much affected by the concentration and the rate of flow of the alcohol solution introduced at the plate. This is especially true in the region of lower (< 2 ppm) bulk concentrations.

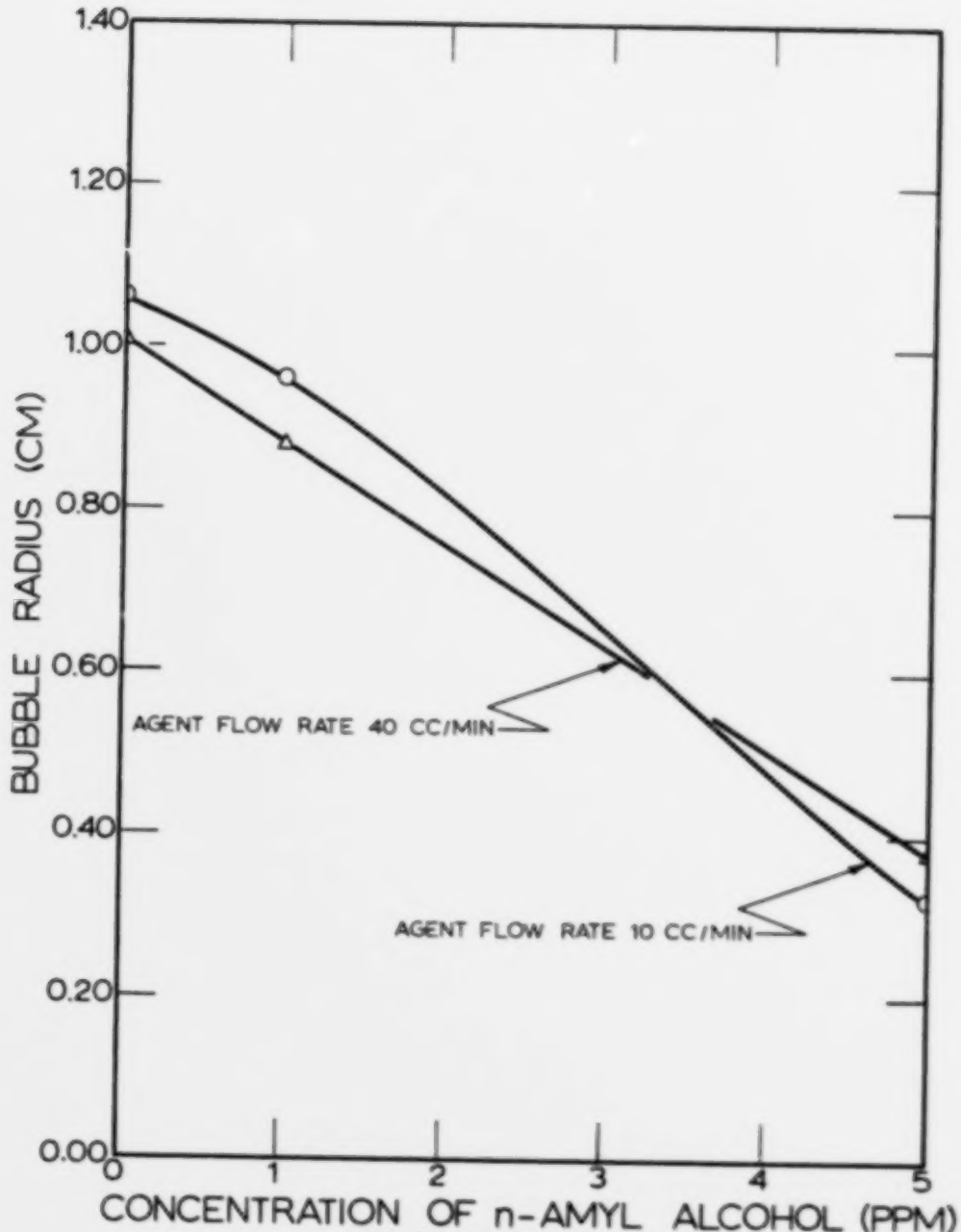

FIGURE 8
BUBBLE RADIUS vs CONCENTRATION OF
n-AMYL ALCOHOL
ALOXITE PLATE WITHOUT COLLAR

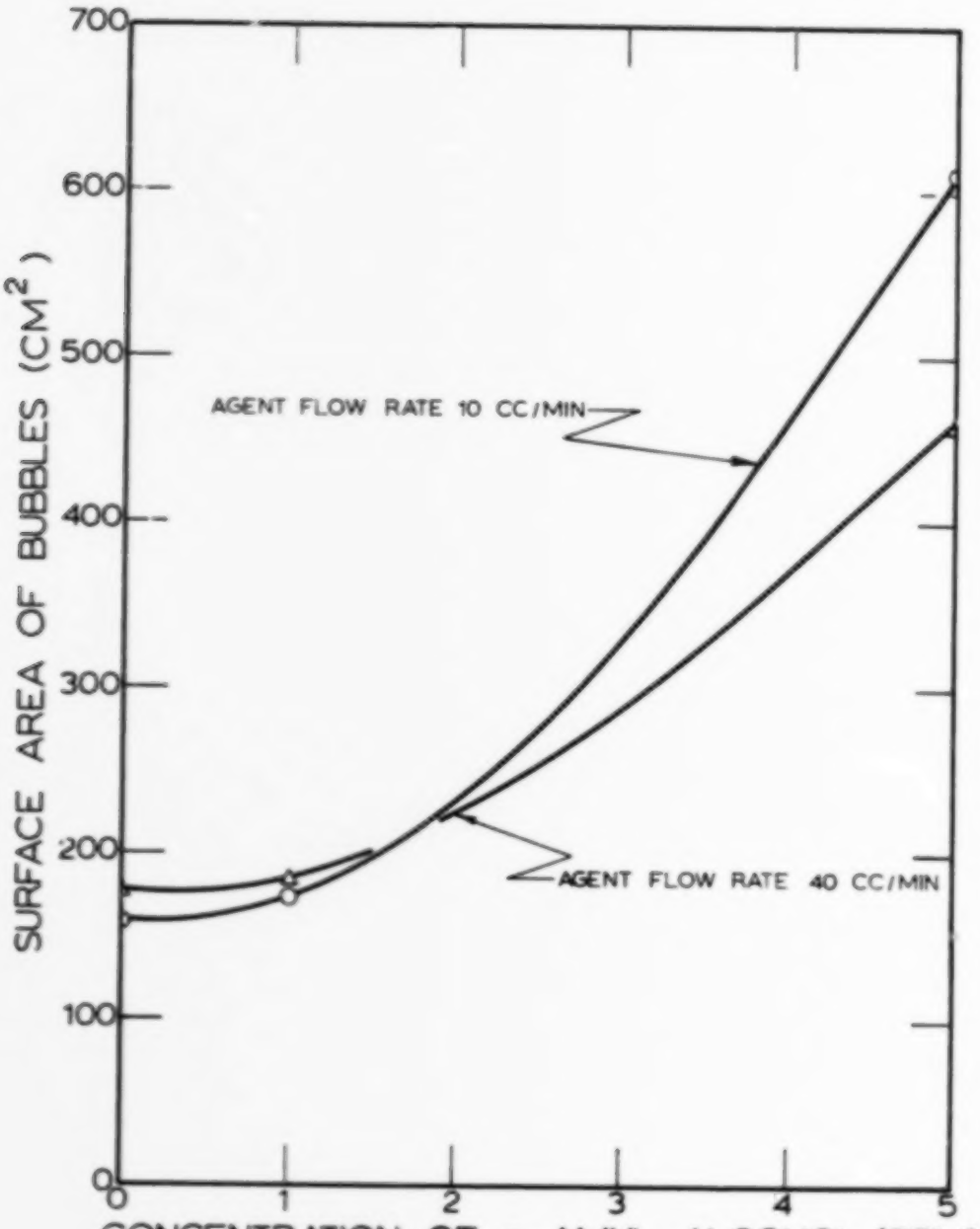

FIGURE 9
SURFACE AREA OF BUBBLES vs
CONCENTRATION OF n-AMYL ALCOHOL
ALOXITE PLATE WITHOUT COLLAR

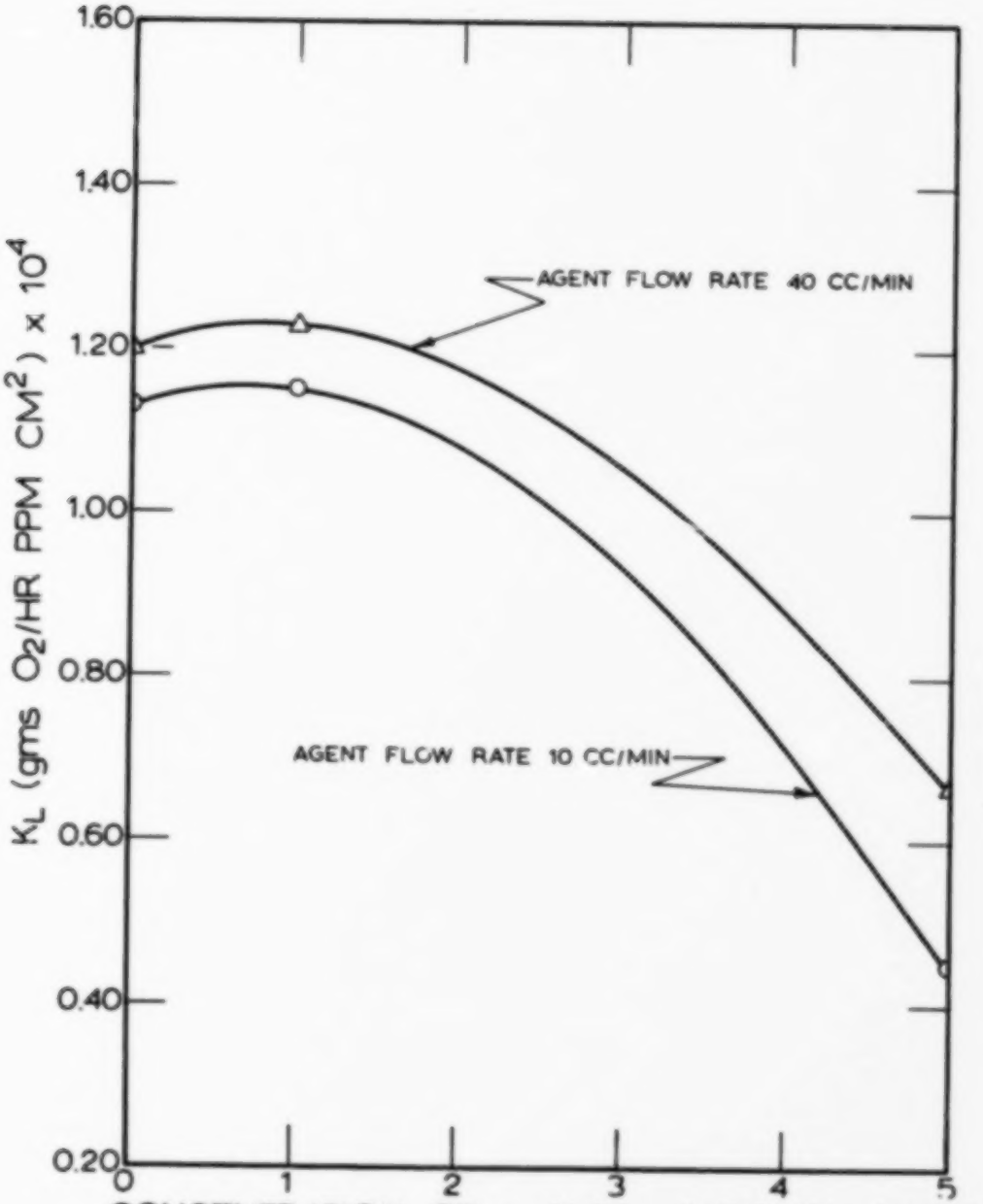

FIGURE 10
K_L vs CONCENTRATION OF
n-AMYL ALCOHOL
ALOXITE PLATE WITHOUT COLLAR

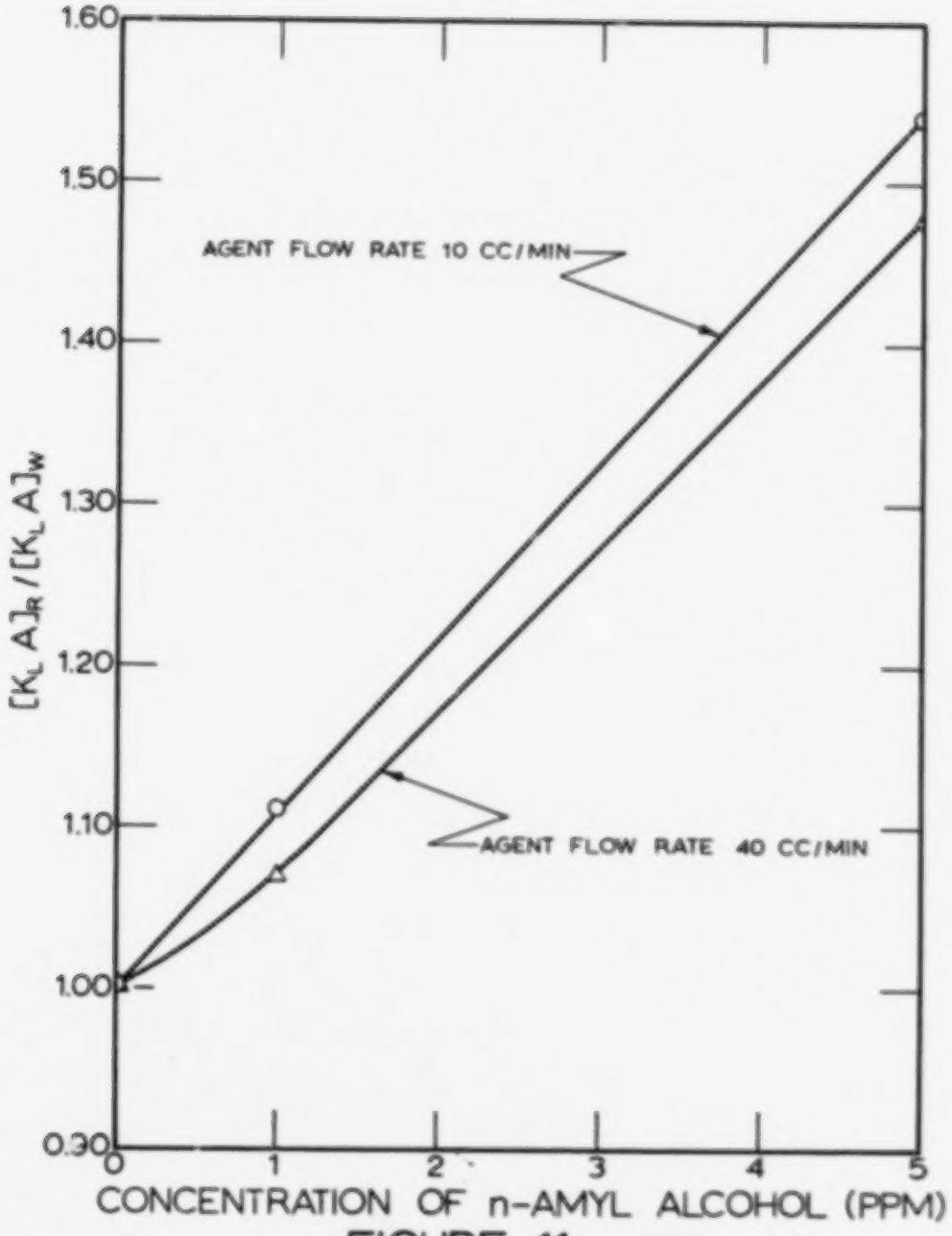

FIGURE 11
$[K_L A]_R / [K_L A]_W$ vs CONCENTRATION OF
n-AMYL ALCOHOL
ALOXITE PLATE WITHOUT COLLAR

At higher bulk concentration (5 ppm) and at the solution flow rate of 10 cc/min the surface area of the bubbles increased from 160 cm^2 in pure water to 610 cm^2 at 5 ppm. At the higher flow rate of 40 cc/min, the surface area increased from 170 cm^2 for pure water to 460 cm^2 at 5 ppm. The above indicates that in this system the higher flow of solution over the porous plate produces a smaller increase of the interfacial area at bulk concentrations higher than 2 ppm. As will be shown later this is in agreement with the results obtained with the Model III.

Similarly the K_L values do not show marked dependence on the rate of flow of the alcohol solution. However, for the higher rate of flow (40 cc/min) they are consistently higher than those for the lower flow rate (10 cc/min). It is possible that the increased turbulence at the plate surface, produced by the higher flow rate, is responsible for this effect.

Figure 11 shows the effects of the rates of flow of the solution on the total oxygen transfer rate referred to that in pure water, $[K_LA]_R/[K_LA]_W$. As could have been anticipated from the behavior of the surface area and K_L at varying flow rates of the solution, the $[K_LA]_R/[K_LA]_W$ values do not depend much on the rates of flow of the solution although they are consistently higher at the lower rates.

Contrary to the behavior of the rotary aerator the effect of the increased surface area of transfer outweighed considerably the decreased mass transfer coefficient, resulting in improvement of the over-all oxygen transfer rate, K_LA, which at bulk concentrations of 1 and 5 ppm increased respectively by about 10 and 50 percent over that in pure water.

The Aloxite Plate with Collar (Model III)

In this model, a plastic collar was installed around the plate to reduce mixing produced by the ascending air bubbles and thus maintain a higher concentration of the agent at the zone of bubble formation.

The results obtained with this model are shown in Figures 12 to 15. All tests of this group were conducted in dilute solution of 4-Methyl-2-Pentanol having a bulk concentration of 1 ppm. The flow rates of the alcohol solution varied from 0 to 58 cc/min and their concentrations were inversely proportional to the rate of flow, to produce the required bulk concentration of 1 ppm. It can be seen from Figure 13 that the rate of flow of the solution has a considerable effect on the interfacial surface area even though the bulk concentration of the aerated solution remains the same. In order to eliminate, in this discussion, the effects of shear produced by the solution at the surface of the plate, a series of tests was conducted in distilled water and with the flow of distilled water over the porous plate.

At a solution flow of 10 cc/min, the interfacial area increased from about 160 cm^2 in distilled water to 320 cm^2 at bulk alcohol concentration of 1 ppm, a hundred percent increase. However, at the highest flow rate of 58 cc/min the surface area increased from 150 to 200 cm^2 which represents an increase of only 33 percent. The above drop of the surface area of the bubbles with increase of the rate of flow of the solution was already noticed in Model II.

However, while the increased flow of the solution had an adverse effect on the interfacial surface area, it improved considerably the values of the oxygen transfer coefficient. Figure 14 shows that while the K_L values in a 1 ppm alcohol solution are lower than those in distilled water they increase

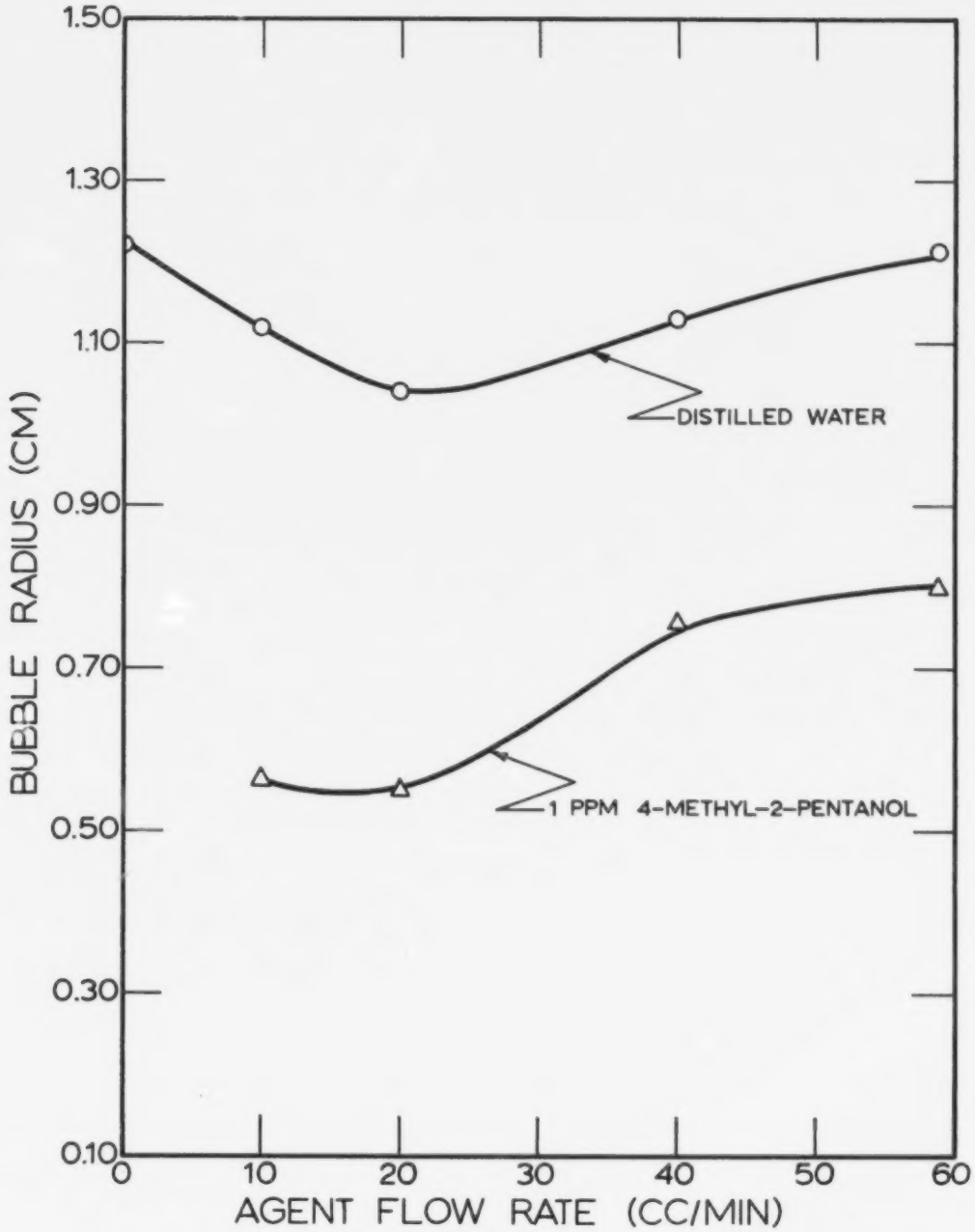

FIGURE 12
BUBBLE RADIUS vs AGENT FLOW RATE
ALOXITE PLATE WITH COLLAR

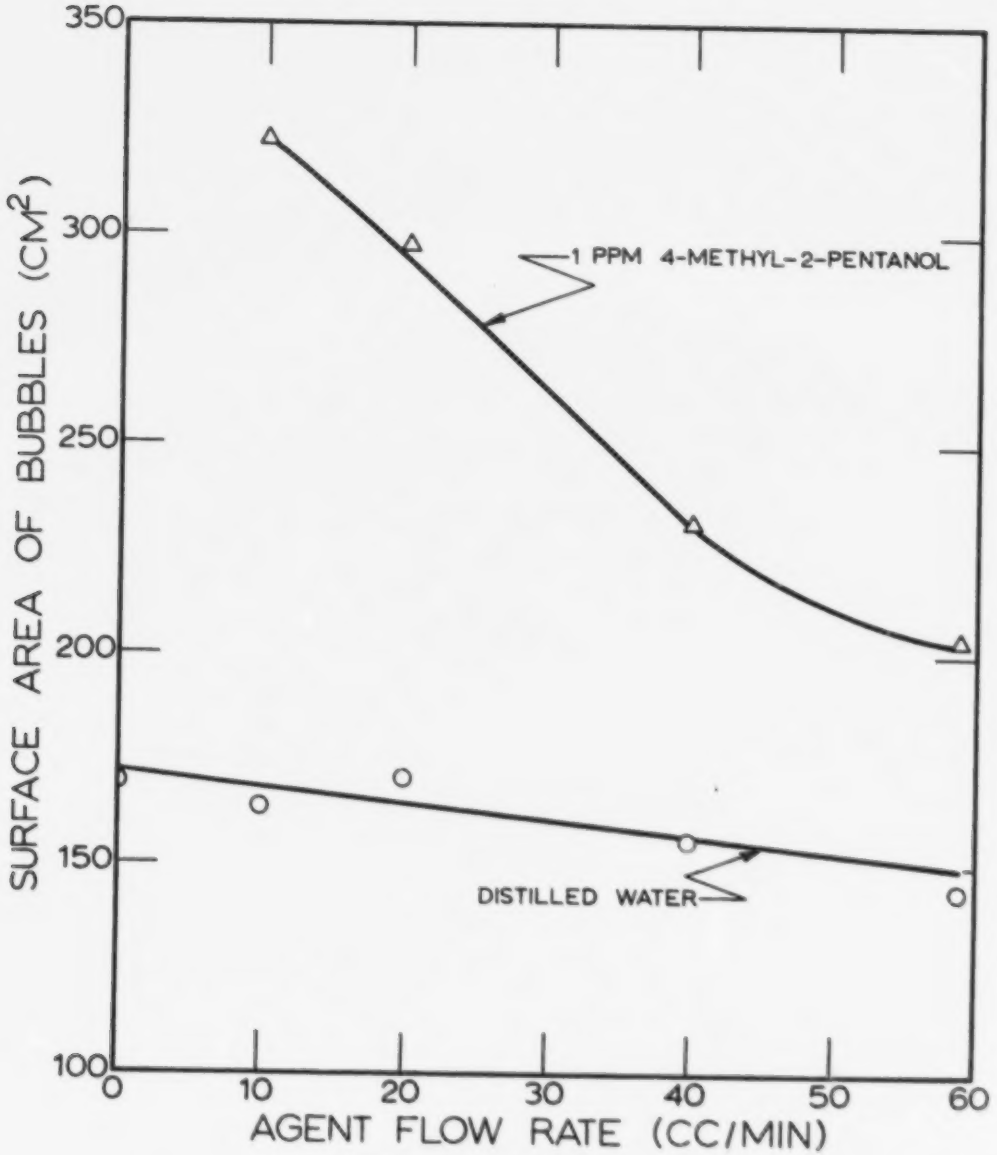

FIGURE 13
SURFACE AREA OF BUBBLES vs
AGENT FLOW RATE
ALOXITE PLATE WITH COLLAR

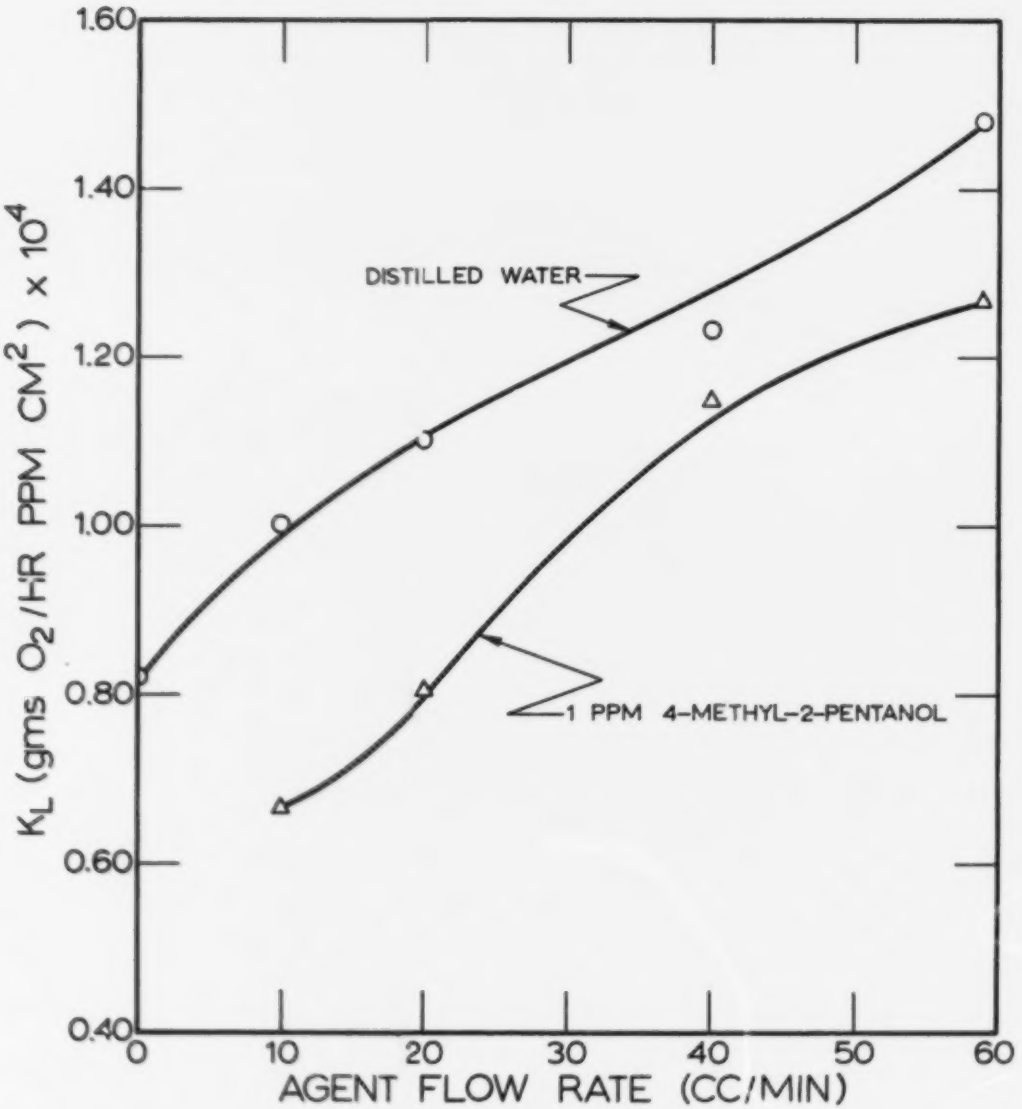

FIGURE 14
K_L vs AGENT FLOW RATE
ALOXITE PLATE WITH COLLAR

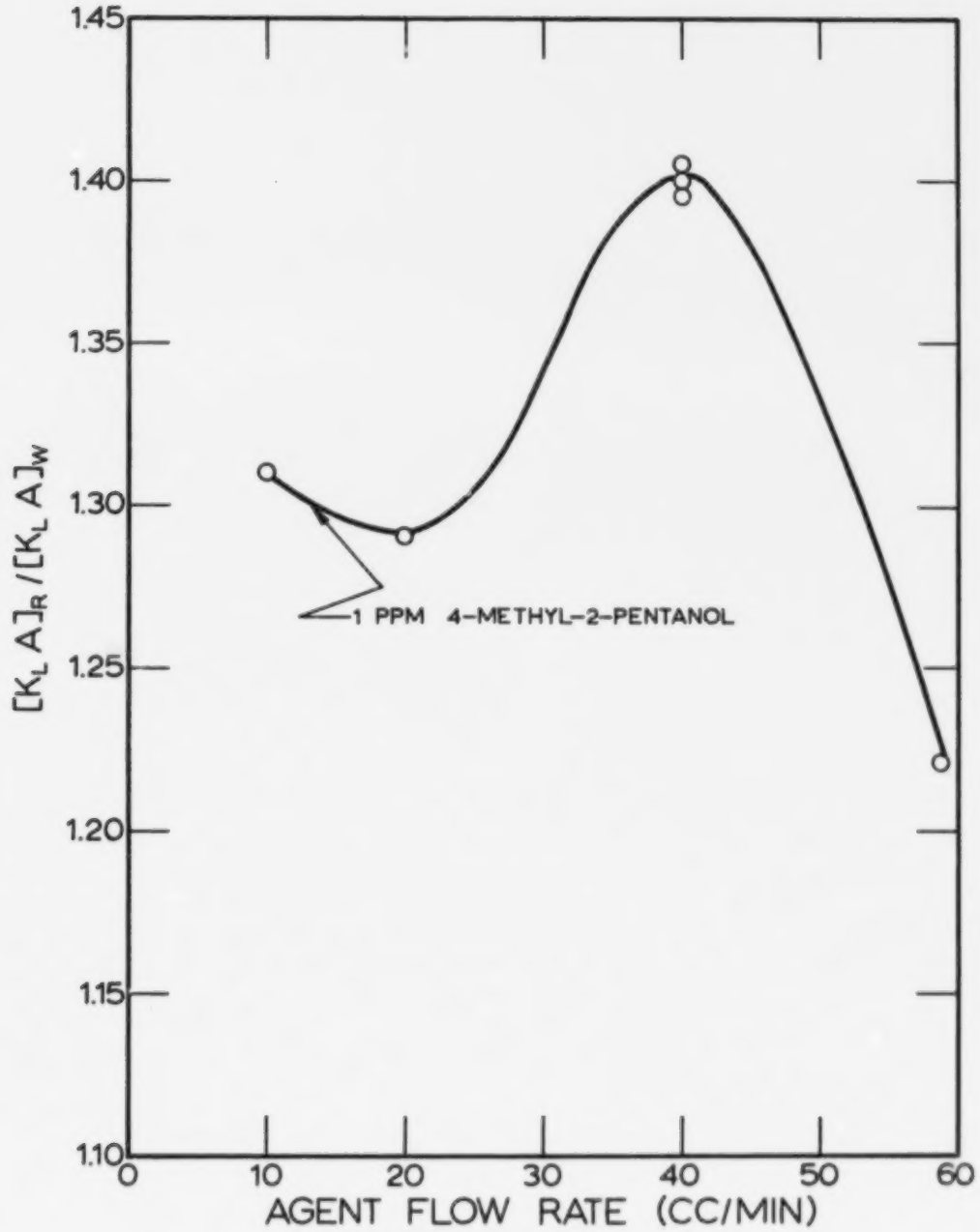

FIGURE 15
$[K_L A]_R / [K_L A]_W$ vs AGENT FLOW RATE
ALOXITE PLATE WITH COLLAR

progressively with the rate of flow over the porous plate; e.g., at a flow rate of 10 cc/min the K_L value was 0.67×10^{-4} while at the highest rate of flow of 58 cc/min, K_L increased to 1.27×10^{-4} despite the same bulk concentration of the alcohol.

Figure 15 shows the effects of the rates of flow of the solution on the total oxygen transfer relative to that in water. The bulk concentration of the solution was 1 ppm of alcohol in all the tests. The curve is a resultant of the two opposing effects which the rate of flow exerts on the interfacial area of the bubbles and on the oxygen transfer coefficient. It shows that increasing the rate of flow of the solution from 10 to 58 cc/min the rate of oxygen absorption relative to water increases, reaching a maximum at 40 cc/min, and then drops sharply with further increase of flow. It is of interest to note that at the maximum the rate of oxygen absorption was increased by 40 percent over that in pure water - a considerable increase, if it is taken into account that the bulk concentration of the alcohol was only 1 ppm.

The results of the tests conducted with Model III showed that operating at constant bulk concentration of the alcohol, the increased flow of the solution reduces considerably the interfacial surface area of the bubbles. This area, however, was always larger than in the corresponding tests conducted in distilled water.

On the other hand, the K_L values increased progressively with the flow rate of solution but were always lower than the corresponding values obtained in distilled water.

A possible explanation of these effects is that the increased flow at the air diffusing surface increased coalescence of the bubbles and thus

decreased the interfacial area. However, at the same time, the greater turbulence resulting from the increased flow had a beneficial effect on the mass transfer coefficient. These effects, although opposing each other, are not the same in magnitude resulting in appearance of a maximum oxygen transfer rate at a certain flow and concentration of the solution.

It must be also stressed that under the conditions used in the tests, the presence of the additive improved the surface area more than it reduced the K_L value. The result was that the over-all oxygen transfer, K_LA, was always higher than in the distilled water.

SUMMARY

The tests conducted with the rotary aerator (Model I) showed that a continuous introduction of the agent solution at the point of air discharge offers no advantage as compared with a batch system (uniform concentration); on the contrary, the K_LA values for the batch system were considerably higher than for the continuous flow of the solution. This is principally due to the striking reduction of the K_L values in the continuous system. The above applies to one aerator speed and one flow rate of solution through the aerator. It is possible that change of these conditions could improve its performance.

The results obtained with Aloxite plate (Model II) and a continuous flow of the agent solution against the plate showed that the performance (K_LA) of this aerator is practically independent of the rate of flow and concentration of the incoming solution. This behavior indicates that no appreciable concentration increase was produced at the plate, probably

because of the vigorous mixing induced by the rising air bubbles.

In Model III, a collar was mounted around the plate to reduce the mixing of the solution entering the plate and the surrounding liquid. All these tests were conducted in the continuous system at a constant bulk concentration of 1 ppm of 4-methyl-2-pentanol and at varying rates of flow and concentration of the alcohol solution entering the plate.

The results obtained with this model showed that in all the tests the alcohol increased considerably the surface area of the bubbles; however, this increase became smaller at higher flow rates of solution. The K_L values showed a completely different behavior. Their values increased progressively with the rate of flow of solution but were always smaller than those in distilled water. The different magnitude of these opposing effects results in appearance of a maximum transfer rate (K_LA) at a certain intermediate rate of flow of the solution. In the investigated system, the K_LA value at the maximum was 40 percent higher than in pure water - a considerable increase if it is considered that the bulk concentration of the alcohol was only 1 ppm. Although the system as such is comparatively efficient, it seems that it could be considerably improved by reducing the adverse effect of the rate of flow of the solution on the interfacial area. It is possible that this effect was due to the fact that the solution was introduced at the plate in the direction opposite to that of the rising bubbles, thus increasing their coalescence. In the next model which is proposed for study the solution will be introduced in the direction of the air flow but through separate conduits mounted in the plate.

NOTATION

A = Total surface area, cm^2

a = Major semi-axis, cm

b = Minor semi-axis, cm

C = D.O. concentration, ppm

C_b = Bulk D.O. concentration at any time, ppm

C_f = D.O. concentration in the overflow water, ppm

C_e = Equilibrium D.O. concentration, ppm

C_o = Initial D.O. concentration at time t_o, ppm

d = Bubble diameter, cm

d_s = Sauter diameter, cm

H = Total air hold-up, cm^3

K_L = Oxyten transfer coefficient, g/hr,cm^2,ppm

$[K_LA]_R/[K_LA]_W$: Over-all mass transfer relative to that in pure water

n = Number of bubbles

q = Oxygen absorption rate, g/hr

V = Rate of flow of water, g/min

W = Weight of water in column, g

α = Eccentricity: $(1 - (\frac{b}{a})^2)^{1/2}$

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